A Novel DC-AC/DC Converter with Boosted AC-DC Output Voltages

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***Abstract*—A single-input double-output converter, which receives a DC voltage and supplies an AC and a DC load, is introduced in this paper. The topology is based on merging a half-bridge DC/AC inverter with a conventional DC/DC boost converter. The DC load supplied in one of the output terminals experiences an increased voltage level compared to that of the input voltage. As for the AC load, the peak amplitude of the voltage is no more limited to half of the input DC voltage and can be controlled to be a larger value. A lookup table based control method using selective harmonic elimination technique is developed to reach the intended output DC and AC voltage levels. Using less number of elements and providing step-up functionality for AC output are the most prominent advantages of the converter. The proposed converter can be used in micro-grids, which comprise numerous types of DC sources and AC/DC consumers. The operation of the DC-AC/DC converter is examined using simulations under different conditions and scenarios.**

Keywords—Hybrid converter, step-up inverter, boost converter, selective harmonic elimination technique

I. INTRODUCTION

The tendency to replace AC voltage sources with DC types is increasing nowadays. Particularly the developments in the field of renewable energy sources, which usually deliver power in DC voltage, accelerate this transition. On the other hand, different AC and DC loads/consumers exist in the grid that require power in a specific voltage form, i.e. in a suitable voltage level and frequency.

Typically, when a DC power source is expected to supply two separate loads, where one is DC and the other one is AC, the configuration shown in Fig. 1(a) is used. In such a topology, two separate converters, i.e. a DC/DC and a DC/AC, are connected in parallel to the input voltage source and deliver power to their corresponding loads. This configuration possesses high reliability since the operation of two converters is completely independent. The control of the whole system is also simple and similar to existing converters of each type. However, low power density is the most disappointing drawback of the solution illustrated in Fig.1 (a). Here is the point, where the concept of hybrid converters arises. The general topology of a hybrid converter is depicted in Fig. 1(b). It can be seen that a hybrid converter is capable of supplying two or more loads, simultaneously. These loads can be AC or DC type with respect to the architecture of hybrid converter.

Renewable energy resources, like photovoltaic systems and fuel cells, normally provide power in a low voltage level and to supply a DC or AC load it is necessary to increase the voltage level. As a result, being capable of operating in step-up mode is a positive characteristic for any converter. In addition, when studying a hybrid converter it must be mentioned that the main impetus to propose the concept of hybrid converters is to increase power density. Equally, it is expected to use less number of semiconductor devices in a hybrid converter compared to a parallel connection based system as shown in Fig. 1 (a).

Ray and Mishra in [1] have introduced a boost derived hybrid converter in which the single switch of a typical boost converter is replaced with an H-bridge structure. The H-bridge structure by itself is capable of supplying an AC load while due to connecting an inductor in series with the input voltage source, it has been possible to turn on both switches in each leg of H-bridge simultaneously and realize shoot-through state. This results in charging the boost inductor and consequently besides the AC voltage, a boosted DC voltage will be provided, too. This sophisticated structure brings inspiration for many authors to investigate hybrid converters. In [2], the same topology of [1] is considered from other viewpoints. Authors in [3] and [4] have proposed Cuk and

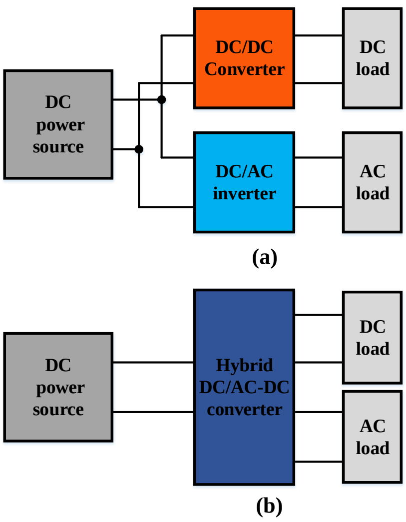


Fig. 1. Supplying separate DC and AC loads with single DC input: (a) conventional solution and (b) using hybrid converter.

SEPIC based hybrid converters, respectively. An additional switch in series with the input voltage is added in [5],[6] to include buck/boost capability. Interleaved hybrid converters are introduced in [7],[8], where in [8] an additional switch is included to not to limit the charging intervals of the inductor to the shoot-through states of the H-bridge. In order to reach a multilevel output AC voltage, in [9] the input voltage is halved and an additional switch is used to connect one of the output AC terminals to midpoint. Hybrid converters concept is extended to multilevel converters in [10], where thirteen switches have been used in the structure. A three-phase hybrid converter with forced continuous conduction mode (FCM) is discussed in [11]. Impedance source converters with hybrid functionality have been studied in [12],[13]. The impedance network discussed in [12] requires additional diodes. The basic idea is modified to reach a transformerless hybrid converter with reduced leakage current in [14]. Multi-port topologies have been introduced in [15],[16]. Two non-isolated DC outputs with an AC output are supplied in [16] while in [15] one of the DC outputs is isolated. Use of hybrid converters in PV systems is investigated in [17],[18]. For multi-coil wireless power transfer applications, a single inductor multi-output buck hybrid converter is developed in [19]. Authors in [20] have proposed a completely different topology to achieve hybrid operation and have halved the input voltage and each half is used to supply a DC load. As for the AC load, one of the terminals is connected to the midpoint and voltage of the other one is controlled by two other switches.

In this paper, the half-bridge inverter is considered since it is capable of providing AC voltage with only two switches. But due to the most severe drawback of the half-bridge inverter, which is limiting the peak amplitude of the output AC voltage to half of the input DC voltage, a pair of inductors are added to increase the voltage level by adding shoot-through states to the operation. At the same time, a DC/DC boost converter will be achievable in the topology as discussed in details in the next sections. Most of hybrid converters do not realize step-up inverter functionality, but in this paper a selective harmonic elimination (SHE) derived method has been applied to reach boosted AC voltage.

This paper is organized as follows; section II introduces the topology of the proposed hybrid converter. Operational modes are studied in section III and output voltages calculation is provided in section IV. The suggested control method is explained in section V. The simulation results are presented in section VI and a comparison among different solutions is carried out in section VII. Finally, section VIII provides a conclusion.

II. Proposed Hybrid Converter's Topology

The topology of the proposed hybrid converter is derived by merging a typical half-bridge and DC/DC boost converter, shown in Fig. 2(a) and (b), respectively. As shown in Fig. 2(a), one of the terminals of the AC output in a half-bridge is connected to the midpoint of a capacitive voltage divider and experiences approximately $\frac{V_{dc}}{2}$ all the time. While the other terminal is connected to the V_{dc} or zero voltage periodically. As a result, the maximum and minimum voltage of one terminal compared to the other one will be $+\frac{V_{dc}}{2}$ and $-\frac{V_{dc}}{2}$, respectively. In other words, the peak to peak voltage value in a half bridge inverter is limited to V_{dc}. Although using less number of switches (two switches) compared to an H-bridge,

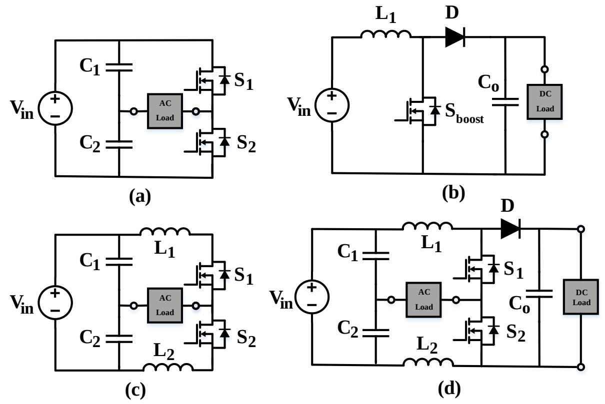


Fig. 2. (a) Conventional h-bridge inverter, (b) conventional DC/DC boost converter, (c) enhanced half-bridge, and (d) proposed hybrid converter.

that requires four switches, is an advantage for the half-bridge inverter, the lower peak to peak voltage is a disappointing drawback that limits the acceptance of half-bridge topology as an inverter.

The basic concept of increasing the voltage level can be understood by studying a conventional boost converter shown in Fig. 2(b). The main idea is to charge an inductor during some intervals and deliver the stored energy in the subsequent interval. This functionality can be implemented in a half-bridge inverter to reach higher voltage levels if the topology of an inverter of this type is retrofitted as Fig. 2(c). Similar to a DC/DC boost converter, the inductors can be charged if both of the switches get turned on simultaneously. Then if only one of the switches is turned off, an increased voltage will be applied on the AC terminal that is more than $\frac{V_{dc}}{2}$ or less than zero if only S_a or S_b conducts, respectively. Hence, the peak to peak voltage will be increased.

Considering the inverter of Fig. 2(c) in details reveals that it is possible to obtain a boosted DC voltage by adding a diode to the structure as Fig. 2 (d), which yields the proposed hybrid converter.

The proposed topology is depicted in Fig. 2(d). In this topology, switches S_1 and S_2 can play the role of S_{boost} if they conduct simultaneously, which is allowed due to placing inductors L_1 and L_2. Besides, inductors L_1 and L_2, which do not exist in a typical half-bridge inverter, are inherited from the boost converter to bring step-up feature to the converter.

III. Operational Modes

The operation of the proposed hybrid converter can be analyzed in three modes with respect to conduction state of the switches S_1 and S_2. Zero mode is defined as the condition in which both switches have been turned on. Mode 1 and mode 2 are referred to states that only S_1 and S_2 are conducting, respectively. Therefore, indices 0, 1, and 2 for any parameter determines the mode of operation. Explanation of converter's operation in each mode is presented in this section.

In order to facilitate the explanation, five nodes have been defined in the converter's circuit as AC1, AC2, A, B, and C. These points can be recognized in Fig. 3. AC1 is one of the AC loads terminals that experiences the voltage $\frac{V_{dc}}{2}$ all the time and AC2 is the other terminal of the AC load that experiences different voltage values in each mode.

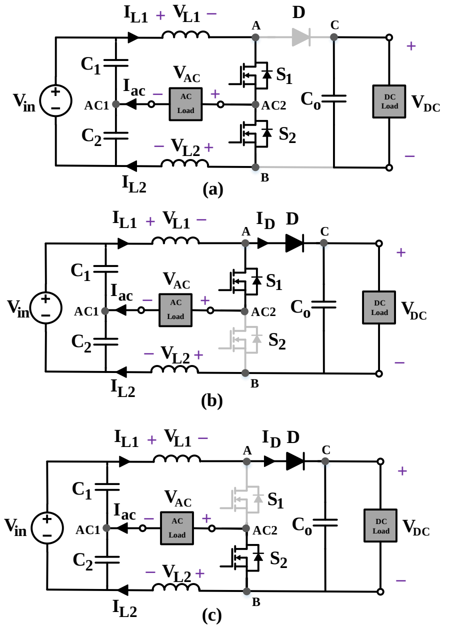


Fig. 3. Operational modes of proposed hybrid converter: (a) mode0, (b) mode1, and (c) mode2.

Mode 0: Fig. 3(a) shows the involved elements in this mode. Switches S_1 and S_2 are turned on simultaneously and the inductors L_1 and L_2 are charged through $L_1S_1S_2L_2$ path. Within this mode, the energy of the input voltage source is stored in the inductors since they experience an increasing current. The diode D is reversed biased and does not conduct since the voltage across L_1 is positive ($\frac{di}{dt} > 0$). In this mode, voltage of the DC capacitor is applied on the DC load. As for the voltage of the AC load, Eq. (1) can be used.

$$\mathrm{v}_{\mathrm{AC2}} = \mathrm{v}_{\mathrm{A}} = \mathrm{v}_{\mathrm{B}} \tag{1}$$

Mode 1: Through this mode, S_2 is turned off but S_1 keeps conducting as shown in Fig. 3(b). Since the charging path of the inductors has been cut out, the current through L_1 and L_2 starts decreasing, i.e. $\frac{di}{dt}$ becomes negative. As a result, the diode D starts conducting. AC2 and C nodes' voltage can be reached using Eq. (2).

$$\mathrm{v}_{\mathrm{C}} = \mathrm{v}_{\mathrm{AC2}} = \mathrm{v}_{\mathrm{A}} \tag{2}$$

Mode 2: This mode is somehow similar to mode 1, but as Fig.3(c) shows, instead of S_1, switch S_2 is turned on and S_1 stops conducting. Similarly, the inductors does not get charged and the diode D conducts. The voltage of the nodes C and AC2 can be achieved using Eqs. (3) and (4).

$$\mathrm{v}_{\mathrm{C}} = \mathrm{v}_{\mathrm{A}} \tag{3}$$

$$\mathrm{v}_{\mathrm{AC2}} = \mathrm{v}_{\mathrm{B}} \tag{4}$$

In the next section, after studying average values and considering the assumptions, the values of v_{A} and v_{B} will be calculated in each mode and the DC and AC voltage values will be obtained.

IV. Average Model and Voltages Calculation

Average values studying is helpful to calculate the value of voltage for each point illustrated in Fig. 3 and consequently achieve DC and AC output voltages in the proposed hybrid converter.

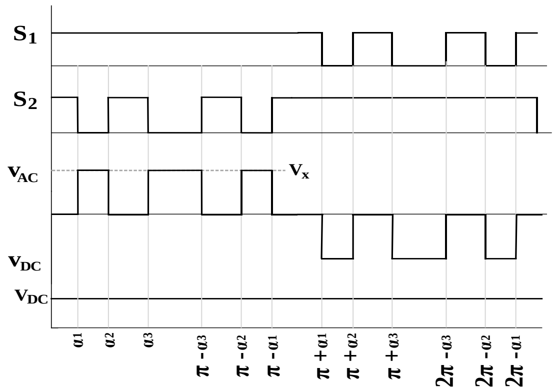


Fig. 4. S_1 and S_2 switches gate pulses and resultant AC and DC output voltages.

A quasi SHE method, as discussed in the following section, is applied to control the converter. Fig. 4 represents the gate pulse of each switch during one period under steady state condition. As can be seen in positive half-cycle of the output AC voltage, the switch S_1 conducts continuously and S_2 is turned on and off frequently. Similarly, during the negative half-cycle, S_2 is on and S_1 is switched between on and off states. The corresponding waveforms of different elements voltage are also depicted in Fig. 4.

A duration ratio for each mode, defined in the previous section, is considered as D_0, D_1, and D_2, which determines the ratio of the sum of all intervals for each mode to the whole period T_s. Clearly one can infer Eq. (5) as the relationship among the duration ratios:

$$\mathrm{D}_1 + \mathrm{D}_2 = 1 - \mathrm{D}_0 \tag{5}$$

The average voltage across each inductor, i.e. V_{L1} and V_{L2} is zero under steady state condition. V_{S1} and V_{S2} stand for the average voltage across switches S_1 and S_2, respectively. V_A, V_B, and V_C are used as average voltage values of points A, B, and C, respectively. Considering the loop including $C_1C_2L_1S_1S_2L_2$ one can reach Eq. (6) as:

$$\mathrm{V}_{\mathrm{C1}} + \mathrm{V}_{\mathrm{C2}} - \mathrm{V}_{\mathrm{L1}} - \mathrm{V}_{\mathrm{S1}} - \mathrm{V}_{\mathrm{S2}} - \mathrm{V}_{\mathrm{L2}} = 0 \tag{6}$$

Obviously $V_{C1}+V_{C2}=V_{in}$ and $V_{L1}+V_{L2}=0$. Then, $V_{S1}+V_{S2}=V_{in}$. Due to the symmetry of the converter's circuit, Eq. (7) is valid in the steady state condition.

$$\mathrm{V}_{\mathrm{S1}} = \mathrm{V}_{\mathrm{S2}} = \frac{\mathrm{V}_{\mathrm{in}}}{2} \tag{7}$$

Since the diode conducts only in modes 1 and 2, then $(D_1+D_2)T_s$ is the time that V_{DC} is applied across S_1S_2. Let's consider the capacitor C_o to be large enough to ensure a constant V_{DC}. Then, one can use Eq. (8) to calculate V_{DC}.

$$\mathrm{V}_{\mathrm{S1}} + \mathrm{V}_{\mathrm{S2}} = (\mathrm{D}_1 + \mathrm{D}_2)\mathrm{V}_{\mathrm{DC}} \tag{8}$$

Using (5), (7), and (8) Eq. (9) is achieved to yield the output DC voltage.

$$\mathrm{V}_{\mathrm{DC}} = \frac{\mathrm{V}_{\mathrm{in}}}{1 - \mathrm{D}_0} \tag{9}$$

Now considering the switching pattern, it can be understood that since S_2 is ON through the second half-cycle, its average voltage in this half-period is zero and because of (7) the average value of V_{S1} during the first half-period has to be V_{in}. Obviously, V_{AC2} equals to V_{S2} and consequently the average value of the AC output port can be calculated using (10).

$$\bar{V}_{AC}|_{[0\ \frac{T}{2}]} = V_{AC2} - V_{AC1} = V_{in} - \frac{V_{in}}{2} = \frac{V_{in}}{2} \quad (10)$$

Due to the symmetry of the circuit, the voltage points AC1 and AC2 is zero for the time $\frac{D_0 T_S}{2}$ during the first half-cycle. Then using (10), Eq. (11) can be used to calculate V_x value shown in Fig. 4.

$$V_x = \frac{V_{in}}{2(1-D_0)} \quad (11)$$

The unique feature of the proposed hybrid converter is realized from (11). In other words, if the conventional half-bridge architecture was used, the value of V_x would be anticipated to be $\frac{V_{in}}{2}$ but herein the $\frac{1}{(1-D_0)}$ coefficient makes it possible to reach higher peak amplitude voltage at AC output.

V. Proposed Control Method

In order to control the proposed hybrid converter, a quasi SHE (selective harmonic elimination) method is suggested. Controlling the converter in this section is aiming to turn on and off switches S_1 and S_2 so that the intended values of V_{DC} and V_{AC} can be achieved. It is useful to review the principle concept of SHE technique.

SHE technique is an improved pulse width modulation (PWM) method. SHE is mainly applied in DC/AC applications and the output AC voltage, before passing through AC filter, is as shown in Fig. 4. To achieve such a waveform in AC port, S_1 and S_2 should be turned on and off as represented in Fig. 4. The controller determines α_i values and there would be any number of these angles considering the process capability of the microprocessor.

In the case of a converter operating under condition as shown in Fig. 4, the value of D_0 is calculated as (12).

$$D_0 = \frac{2}{\pi}\left[\sum_{i \text{ is odd value}} \alpha_i - \sum_{j \text{ is even value}} \alpha_j\right] \quad (12)$$

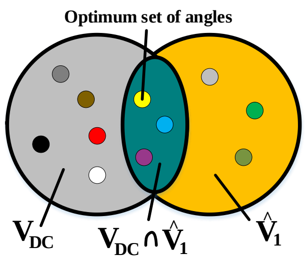


Fig. 5. Preparing the lookup table and selecting optimum angles for each pair of output AC and DC voltages.

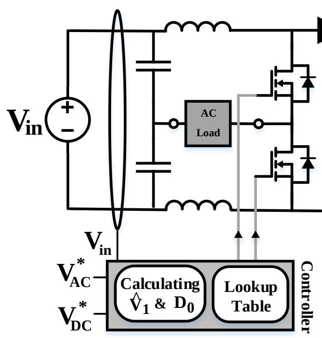


Fig. 6. Controller's basic operation explanation.

Obtaining the Fourier series of the output AC voltage yields Eq. (13) to calculate amplitude of the fundamental and harmonic components.

$$\hat{V}_k = \frac{4V_x}{k\pi}\left[\sum_{i \text{ is odd value}} \cos(k\alpha_i) - \sum_{j \text{ is even value}} \cos(k\alpha_j)\right] \quad (13)$$

Where k is the number of components and in the case of proposed hybrid converter V_x is derived using (11). Hence, the peak amplitude of the fundamental component is achieved as Eq. (14).

$$\hat{V}_1 = \frac{2V_{in}}{\pi\left(1-\frac{2}{\pi}\left[\sum_{i \text{ is odd value}}\alpha_i - \sum_{j \text{ is even value}}\alpha_j\right]\right)}\left[\sum_{i \text{ is odd value}} \cos(\alpha_i) - \sum_{j \text{ is even value}} \cos(\alpha_j)\right] \quad (14)$$

In the suggested quasi SHE method, Eq.(12) and (14) are used to control the values of output DC and AC voltages. If the number of applied angles, i.e. α_is, is n, there would be (n-2) other equations using (13). Obviously, for a given V_{DC} and V_{AC} there may be more than one group of possible α_i values that satisfy the desired equations, Eqs. (13) and (14). The logic to decide which group of α_i values shall be chosen, is illustrated in the diagram of Fig. 5. Each group of α_i values is shown as a dot. The gray circle is the set of α_i angles that give desired D_0 to achieve an intended value of V_{DC} using (9). On the other hand, the orange circle includes all α_i values that yield a specific $\hat{V}_1$ value. The intersection of the gray and orange circle, shown in green color, is the set of whole α_i values that can supply V_{DC} and $\hat{V}_1$ in the output ports of the hybrid converter for a known input voltage. The yellow point in the green area is the α_i values set that results the minimum total harmonic distortion compared to others as supplying V_{DC} and $\hat{V}_1$.

The suggested control method is based on using a look-up table, which include the optimum α_i values for each pair of desired output DC and AC voltages. The schematic illustration of the control algorithm is shown in Fig. 6.

VI. Simulation Results

In order to examine the functionality of the proposed hybrid converter some simulations have been carried out in different scenarios. The characteristics and parameters in the simulations are listed in table I. Also, table II provides the conditions in the studied scenarios.

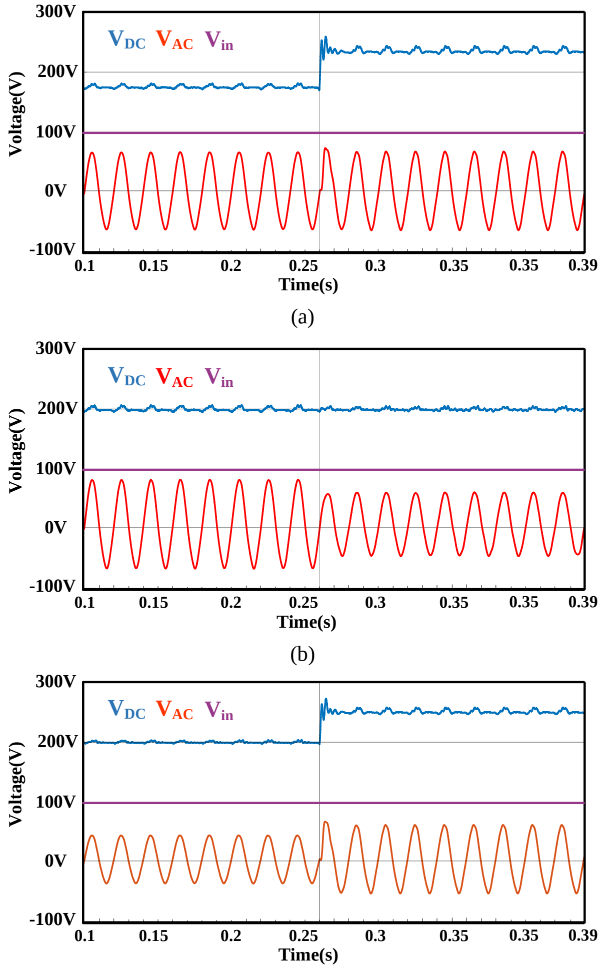
In the first scenario, the AC output is expected to keep constant while DC output must be increased. Fig. 7 (a) shows

Table I. Characteristics and the parameters of the converter

input voltage	100V
number of controlling angles	15
loads at AC and DC ports	30Ω
boosting inductors	300µH
AC output frequency	50Hz

Table II. Conditions in each scenario

scenario	till t = 0.26s		after t = 0.26s	
	V_{DC}	V_{AC_peak}	V_{DC}	V_{AC_peak}
I	180V	80V	230V	80V
II	200V	80V	200V	50V
III	200V	50V	250V	70V



(a) (b) (c)

Fig. 7. Simulation results: (a) DC output changing from 180V to 230V and constant 80V peak AC output constant, (b) constant 200V DC output and peak AC output changing from 80V to 50V, (c) DC output changing from 200V to 250V and peak AC output changing from 50V to 70V.

the simulation results in this condition, where DC voltage is increased from 180V to 230V but AC output has constant 80V peak voltage. As for the scenario II, despite the first scenario DC voltage must be maintained constant when it is required to change AC output voltage. As shown in Fig. 7 (b), by selecting proper set of angles, it becomes possible to keep DC output at 200V while peak AC output is decreased from 80V to 50V. The third scenario investigates the condition in which both AC and DC output voltages have to be changed simultaneously. Fig. 7 (c) shows the simulation results corresponding to this scenario, where DC output is increased from 200V to 250V and peak AC output is changed from 50V to 70V.

VII. Comparisons

The proposed hybrid converter is not the only converter of this type and many sophisticated and interesting topologies have been introduced which typically use the hybrid converter proposed in [1]. Besides, using separate DC/DC and DC/AC converters can be considered as another suggestion.

It is useful to draw an analogy among some features of the proposed hybrid converter and other solutions for the same application. Required material to compare different topologies is included in table III.

Table III. Comparison among existing solution for simultaneous AC and DC load supplying

method	Switches	DC/AC quality	DC/DC quality	controlling complexity
Proposed	2	buck/boost	boost	high
[1]	4	buck	boost	medium
Separate converters	5	buck	buck/boost	low
[5]	5	buck	buck/bust	medium
[7]	5	buck	boost	medium

The main advantage of the proposed converter is the high power density because of using the least number of switches. The other advantage is being capable to bring step-up operation for DC/AC conversion. Table III, also reveals that the main drawback of the proposed converter is the complexity of its control. However, using a quasi SHE method makes it possible to achieve wider ranges of AC and DC outputs, due to requiring a lookup table it may be considered complex. The other shortcoming is disability in step-down operation for DC output, which is not so critical as most of applications require step-up operation.

VIII. Conclusion

A novel hybrid converter suitable to be used in microgrids has been proposed in this paper. The topology is realized by merging a DC/DC boost converter and a half-bridge DC/AC inverter. The converter is capable of supplying two loads, one a DC and the other one an AC load, simultaneously from a common DC input source. A quasi SHE method has been suggested to control the hybrid converter. The control method makes the converter to be able to provide desired output DC and AC voltage values as minimizing the harmonic components. Simulations under different voltage demands at both DC and AC output ports validated the expected operation of the converter. Requiring less number of semiconductor devices compared to other possible solution is the prominent feature of proposed hybrid converter that brings high power density and low cost. The other advantage of the converter is its step-up/down operation for the AC output port that makes it possible to respond to a wider range of AC loads. Investigating simpler control methods can be precious.

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